

The long-term survival chances of young massive star clusters

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Abstract I review the long-term survival chances of young massive star clusters (YMCs), hallmarks of intense starburst episodes often associated with violent galaxy interactions. In particular, I address the key question as to whether at least some of these YMCs can be considered proto-globular clusters (GCs). In the absence of significant external perturbations, the key factor determining a cluster's long-term survival chances is the shape of its stellar initial mass function. I conclude that there is an increasing body of evidence that GC formation appears to be continuing until today; their long-term evolution crucially depends on their environmental conditions, however.

Keywords open clusters and associations: general, galaxies: star clusters, galaxies: interactions, Magellanic Clouds, galaxies: starburst

1 Young mass star clusters as proto-globulars

Young, massive star clusters (YMCs) are the hallmarks of violent star-forming episodes triggered by galaxy collisions and close encounters. Their contribution to the total luminosity induced by such extreme conditions completely dominates the overall energy output due to the interaction-induced star formation (e.g., de Grijs & Parmentier 2007; and references therein).

The question remains, however, whether or not at least a fraction of the compact YMCs seen in abundance in extragalactic starbursts, are potentially the

progenitors of ($\gtrsim 10$ Gyr) old globular cluster (GC)-type objects – although of higher metallicity than the present-day GCs. If we could settle this issue convincingly, one way or the other, such a result would have far-reaching implications for a wide range of astrophysical questions, including our understanding of the process of galaxy formation and assembly, and the process and conditions required for star (cluster) formation. Because of the lack of a statistically significant sample of YMCs in the Local Group, however, we need to resort to either statistical arguments or to the painstaking approach of case-by-case studies of individual objects in more distant galaxies.

1.1 The stellar initial mass function

The evolution to old age of young clusters depends crucially on their stellar initial mass function (IMF). If the IMF slope is too shallow, i.e., if the clusters are significantly deficient in low-mass stars compared to, e.g., the solar neighbourhood, they will likely disperse within about a Gyr of their formation (e.g., Chernoff & Shapiro 1987; Chernoff & Weinberg 1990; Goodwin 1997b; Smith & Gallagher 2001; Mengel et al. 2002). As a case in point, Goodwin (1997b) simulated the evolution of $\sim 10^4 - 10^5 M_\odot$ YMCs similar to those observed in the LMC, with IMF slopes $\alpha = 2.35$ (Salpeter 1955; where the IMF is characterised as $\phi(m_*) \propto m_*^{-\alpha}$, as a function of stellar mass, m_*) and $\alpha = 1.50$, i.e., roughly covering the range of (present-day) mass function slopes observed in LMC clusters at the time he performed his N -body simulations (see also de Grijs et al. 2002a,b). The stellar mass range covered ranged from 0.15 to 15 M_\odot ; his N -body runs spanned at most a few 100 Myr. Following Chernoff & Weinberg (1990), and based on a detailed comparison between the initial conditions for the LMC YMCs derived in Goodwin (1997b) and the survival chances of massive star

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clusters in a Milky Way-type gravitational potential (Goodwin 1997a), Goodwin (1997b; see also Takahashi & Portegies Zwart 2000, their fig. 8) concluded that – for Galactocentric distances $\gtrsim 12$ kpc – some of his simulated LMC YMCs should be capable of surviving for a Hubble time if $\alpha \geq 2$ (or even $\gtrsim 3$; Mengel et al. 2002), but not for shallower IMF slopes for any reasonable initial conditions (cf. Chernoff & Shapiro 1987; Chernoff & Weinberg 1990). More specifically, Chernoff & Weinberg (1990) and Takahashi & Portegies Zwart (2000), based on numerical cluster simulations employing the Fokker-Planck approximation, suggest that the most likely survivors to old age are, additionally, characterised by King model concentrations, $c \gtrsim 1.0 - 1.5$. Mengel et al. (2002; their fig. 9) use these considerations to argue that their sample of YMCs observed in the Antennae interacting system might survive for at least a few Gyr, but see de Grijs et al. (2005), and Bastian & Goodwin (2006) and Goodwin & Bastian (2006), for counterarguments related to environmental effects and to variations in the clusters’ (effective) star-formation efficiencies (SFEs), respectively.

In addition, YMCs are subject to a variety of additional internal and external drivers of cluster disruption. These include internal two-body relaxation effects, the nature of the stellar velocity distribution function, the effects of stellar mass segregation, disk and bulge shocking, and tidal truncation (e.g., Chernoff & Shapiro 1987; Gnedin & Ostriker 1997). All of these act in tandem to accelerate cluster expansion, thus leading to cluster dissolution – since expansion will lead to greater vulnerability to tidally-induced mass loss.

1.2 Survival Diagnostics: the Mass-to-Light Ratio versus Age Diagram

With the ever increasing number of large-aperture ground-based telescopes equipped with state-of-the-art high-resolution spectrographs and the wealth of observational data provided by the *Hubble Space Telescope*, we may now finally be getting close to resolving the issue of potential YMC longevity conclusively. To do so, one needs to obtain (i) high-resolution spectroscopy, in order to obtain dynamical mass estimates, and (ii) high-resolution imaging to measure their sizes (and luminosities). As a simple first approach, one could then construct diagnostic diagrams of YMC mass-to-light (M/L) ratio versus age, and compare the YMC loci in this diagram with simple stellar population (SSP) models using a variety of IMF descriptions (cf. Smith & Gallagher 2001; Mengel et al. 2002; Bastian et al. 2006; Goodwin & Bastian 2006). In Fig. 1 I present an updated version of the M/L ratio versus age diagram, including all of the YMCs for which the required

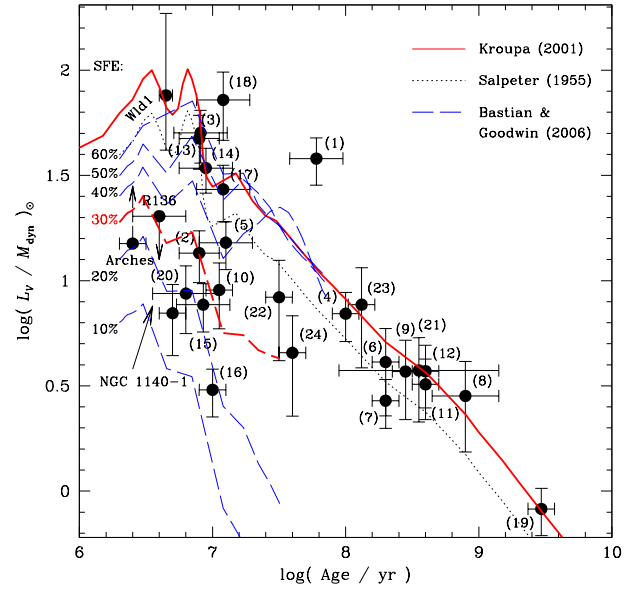


Fig. 1 Updated version of the YMC M/L ratio versus age diagnostic diagram. The numbered data points were taken from Bastian et al. (2006; and references therein); overplotted are the SSP predictions for a Salpeter (1955) and a Kroupa (2001) stellar IMF. We have included four new YMCs, NGC 1140-1 (Moll et al. 2007) the Galactic Centre Arches cluster, R136 in 30 Doradus (Goodwin & Bastian 2006) and Westerlund 1 (denoted ‘Wld 1’; see de Grijs & Parmentier 2007). The evolution expected for SSPs governed by IMFs as defined by both Salpeter (1955) and Kroupa (2001) is shown as the solid and short-dashed lines, respectively. The long-dashed lines represent the evolution expected for SSPs with a Kroupa (2001)-type IMF, but a range of effective star-formation efficiencies (Goodwin & Bastian 2006)

observables are presently available (see also de Grijs & Parmentier 2007). However, such an approach, while instructive, has serious shortcomings. The viability of this approach depends, in essence, on the validity of the virial equation to convert line-of-sight velocity dispersions, σ_{los} , to dynamical mass estimates, M_{dyn} , via (Spitzer 1987):

$$M_{\text{dyn}} = \frac{\eta \sigma_{\text{los}}^2 r_{\text{h}}}{G} \quad , \quad (1)$$

where $r_{\text{h}} = 1.3 R_{\text{eff}}$ are the half-mass and effective (or half-light) radii of the cluster, respectively, and $\eta = 3a$; $a \approx 2.5$ is the factor required to convert the half-mass to the gravitational radius, r_{g} . More specifically, following Fleck et al. (2006), we write

$$r_{\text{g}} = \frac{5}{2} \times \frac{4}{3} r_{\text{h}} \quad , \quad (2)$$

where the factor $5/2$ provides an approximate conversion for a large range of clusters characterised by King (1966) mass profiles; the second numerical factor in Eq. (2) results from projection on the sky, assuming that light traces mass throughout the cluster. The use of both Eq. (1) and the M/L ratio versus age diagram rely on a number of assumptions and degeneracies, however, which I will discuss in some detail below.

1.2.1 IMF degeneracies

In the simplest approach, in which one compares the YMC loci in the M/L ratio versus age diagram with SSP models, the data can be described by *both* variations in the IMF slope *and* variations in a possible low-mass cut-off (e.g., Sternberg 1998; Smith & Gallagher 2001; Mengel et al. 2002); the models are fundamentally degenerate for these parameters. For instance, Sternberg (1998) derived for the YMC NGC 1705-I that it must either have a flat mass function ($\alpha < 2$) or a low-mass truncation between 1 and $3 M_{\odot}$ (see also Smith & Gallagher 2001); in both cases, it is unlikely that this cluster may be capable of surviving for a Hubble time.

However, the conclusion that the IMFs of such starburst clusters may be unusual must be regarded with caution. As Smith & Gallagher (2001) point out, previous claims for highly abnormal (initial) mass functions have often proven incorrect. If anything, the shape of the mass function may vary on the size scales of the individual clusters, but once one considers their birth environments on larger scales the present-day mass function appears to be remarkably robust (e.g., Scalo 1998; Kroupa 2001), with the possible exception of the resolved starburst clusters in the Milky Way (e.g., Stolte et al. 2005, 2006), NGC 3603 and – in particular – the Galactic Centre Arches cluster.

Despite this controversy (particularly for some of the youngest clusters), it appears that most of the YMCs for which high-resolution spectroscopy is available are characterised by ‘standard’ Salpeter (1955) or Kroupa (2001) IMFs (e.g., Larsen et al. 2001; McCrady, Gilbert & Graham 2003; Maraston et al. 2004; Larsen, Brodie & Hunter 2004; Larsen & Richtler 2004; Bastian et al. 2006; see also de Grijs et al. [2005] for a comparison of dynamical and photometric masses, the latter based on ‘standard’ IMF representations).

1.2.2 Mass segregation

While the assumption that these objects are *approximately* in virial equilibrium is probably justified at ages greater than a few $\times 10^7$ yr and for realistic SFEs $\gtrsim 30$ per cent (at least for the stars dominating the light;

see, e.g., Goodwin & Bastian 2006), the *central* velocity dispersion (as derived from luminosity-weighted high-resolution spectroscopy) does not necessarily represent a YMC’s total mass. It is now well-established that almost every YMC exhibits significant mass segregation from very young ages onwards, so that the effects of mass segregation must be taken into account when converting central velocity dispersions into dynamical mass estimates (see also Fleck et al. 2006; Moll et al. 2007).

By ignoring the effects of mass segregation, as is in essence done if one simply applies Eq. (1), the underlying assumption is then that of an isotropic stellar velocity distribution, i.e., $\sigma_{\text{total}}^2 = 3\sigma_{\text{los}}^2$, where σ_{total}^2 is the cluster’s mean three-dimensional velocity dispersion. In the presence of (significant) mass segregation in a cluster, the central velocity dispersion will be dominated by the higher-mass stars populating the cluster core. If we focus on dynamical evolution as the dominant cause of mass segregation in clusters (as opposed to the possible preferential formation of the higher-mass stars close to the cluster core, also known as ‘primordial’ mass segregation; e.g., Bonnell & Davies 1998; de Grijs et al. 2002a), it follows that for the high-mass stars to migrate to the cluster core, i.e., to the bottom of the gravitational potential well, they must have exchanged some of their kinetic energy with their lower-mass counterparts on more extended orbits. As a consequence, the velocity dispersion dominating the observed high-resolution spectra will be *lower* than expected for a non-mass-segregated cluster of the same mass. In addition, measurements of r_h will also be biased to smaller values, and not to the values associated with the cluster as a whole. Mass segregation will thus lead to an *underestimate* of the true cluster mass.

I also note that the assumption of virial equilibrium only holds to a limited extent, even in old GCs, because cluster-wide relaxation time-scales of massive GC-type objects are of order 10^9 yr or longer (Djorgovski 1993). In fact, full global, or even local, energy equipartition among stars covering a range of masses is never reached in a realistic star cluster, not even among the most massive species (e.g., Inagaki & Saslaw 1985; Hunter et al. 1995). As the dynamical evolution of a cluster progresses, low-mass stars will, on average, attain larger orbits than the cluster’s higher-mass stars, and the low-mass stars will thus spend most of their time in the cluster’s outer regions, at the extremes of their orbits. For this reason alone, we would not expect to achieve global energy equipartition in a cluster.

The time-scale for the onset of significant dynamical mass segregation is comparable to the cluster’s dynamical relaxation time (Spitzer & Shull 1975; Inagaki &

Saslaw 1985; Bonnell & Davies 1998; Elson et al. 1998). A cluster’s characteristic time-scale may be taken as its half-mass (or median) relaxation time, i.e., the relaxation time at the mean density for the inner half of the cluster mass for cluster stars with stellar velocity dispersions characteristic for the cluster as a whole (Spitzer & Hart 1971; Lightman & Shapiro 1978; Meylan 1987; Malumuth & Heap 1994).

Although the half-mass relaxation time characterises the dynamical evolution of a cluster as a whole, significant differences are expected locally within the cluster. The relaxation time-scale will be shorter for higher-mass stars than for their lower-mass companions; numerical simulations of realistic clusters confirm this picture (e.g., Aarseth & Heggie 1998; Kim et al. 2000; Portegies Zwart et al. 2002). From this argument it follows that dynamical mass segregation will also be most rapid where the local relaxation time is shortest, i.e., near the cluster centre (cf. Fischer et al. 1998; Hillenbrand & Hartmann 1998). Thus, significant mass segregation among the most massive stars in the cluster core occurs on the local, central relaxation time-scale (comparable to just a few crossing times; cf. Bonnell & Davies 1998).

The combination of these effects will lead to an increase of the dimensionless parameter η in Eq. (1) with time, if the characteristic two-body relaxation time of a given (massive) stellar species is short (Boily et al. 2005; Fleck et al. 2006), and thus to an *underestimate* of the true cluster mass. However, we note that Goodwin & Bastian (2006) point out that a large fraction of the youngest clusters in the M/L ratio versus age diagram appear to have dynamical masses well in excess of their photometric masses, and that, therefore, the result of Boily et al. (2005) and Fleck et al. (2006) does not seem applicable to these YMCs.

1.2.3 Stellar masses

Estimating dynamical masses, M_{cl} , via Eq. (1) assumes, in essence, that all stars in the cluster are of equal mass. This is clearly a gross oversimplification, which has serious consequences for the resulting mass estimates. The straightforward application of the virial theorem tends to *underestimate* a system’s dynamical mass by a factor of ~ 2 compared to more realistic multi-mass models (e.g., Mandushev, Spassova & Staneva 1991; based on an analysis of the observational uncertainties). Specifically, Mandushev et al. (1991) find that the mass-luminosity relation for GCs with mass determinations based on multi-component King-Michie models (obtained from the literature) lies parallel to that for single-mass King models, but offset by $\Delta \log M_{\text{cl}}(M_{\odot}) \simeq 0.3$ towards higher masses.

Farouki & Salpeter (1982) already pointed out that cluster relaxation and its tendency towards stellar energy equipartition is accelerated as the stellar mass spectrum is widened; mass segregation will then take place on shorter time-scales than for single-component (equal-mass) clusters, and thus this will once again lead to an *underestimate* of the true cluster mass (see also Goodwin 1997a; Boily et al. 2005; Fleck et al. 2006; Kouwenhoven & de Grijs 2008, for multi-mass N -body approaches).

We also point out that if the cluster contains a significant fraction of primordial binary and multiple systems, these will act to effectively broaden the mass range and thus also speed up the dynamical evolution of the cluster (e.g., Fleck et al. 2006; Kouwenhoven & de Grijs 2008).

2 Cluster disruption at early times

The early evolution of the star cluster population in the Small Magellanic Cloud (SMC) has been the subject of considerable recent attention and vigorous debate (e.g., Rafelski & Zaritsky 2005; Chandar, Fall & Whitmore 2006; Chiosi et al. 2006; Gieles, Lamers & Portegies Zwart 2007). The key issue of contention is whether the SMC’s star cluster system has been subject to the significant early cluster disruption processes observed in ‘normal’, interacting and starburst galaxies commonly referred to as ‘infant mortality’ (e.g., Lada & Lada 2003; Whitmore 2004; Bastian et al. 2005; Fall, Chandar & Whitmore 2005; Mengel et al. 2005; see also Whitmore, Chandar & Fall 2007) and ‘infant weight loss’. Chandar et al. (2006) argue that the SMC has been losing up to 90 per cent of its star clusters per decade of age, at least for ages from $\sim 10^7$ up to $\sim 10^9$ yr, whereas Gieles et al. (2007) conclude that there is no such evidence for a rapid decline in the cluster population, and that the decreasing number of clusters with increasing age is simply caused by fading of their stellar populations. They contend that the difference between their results was due to Chandar et al. (2006) assuming that they were dealing with a mass-limited sample, whereas it is actually magnitude-limited. In fact, this is not entirely correct; Chandar et al. (2006) analyse the full magnitude-limited sample and conclude that it is approximately surface-brightness limited. They then compare the cluster age distribution of the full sample (expressed in units of dN_{cl}/dt , i.e., the number of clusters per unit time period) to that of a subsample for masses $\geq 10^3 M_{\odot}$ (which they do not analyse in the same manner), and suggest both to be similar, although the latter is much flatter, hence giving rise to the discrepancy between their results and those of Gieles et

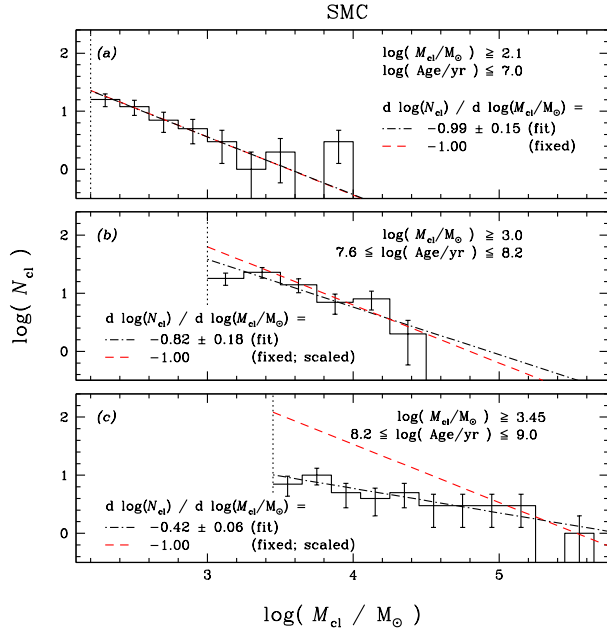


Fig. 2 CMFs for statistically complete SMC cluster subsamples. Age and mass ranges are indicated in the panel legends; the vertical dotted lines indicate the lower mass (50 per cent completeness) limits adopted. Error bars represent simple Poissonian errors, while the dashed lines represent CMFs of slope $\alpha = 2$, shifted vertically as described in the text. The dash-dotted lines represent the best-fit CMFs over the relevant mass range (see de Grijs & Goodwin 2007)

al. (2007). Both studies are based on the same data set, the Magellanic Clouds Photometric Survey (MCPS; Zaritsky, Harris & Thompson 1997).

In de Grijs & Goodwin (2007), we set out to shed light on this controversy surrounding the early evolution and disruption of star clusters in the SMC. We embarked on a fresh approach to the problem, using an independent, homogeneous data set of *UBVR* imaging observations, from which we obtained the cluster age distribution in a self-consistent manner. We present the cluster mass functions (CMFs; i.e., the number of clusters per unit mass range) for subsets of our SMC cluster sample in Fig. 2, where the cluster subsamples were selected based on their age distributions (see de Grijs & Goodwin 2007). In all panels of Fig. 2, we have overplotted CMFs with the canonical slope of $\alpha = 2$ (corresponding to a slope of -1 in units of $d \log(M_{cl}/M_{\odot})/d \log(N_{cl})$, used in these panels). We have only shifted and scaled these lines vertically, as justified below.

We emphasise that we need to choose the age ranges of our cluster subsamples carefully, for both physical reasons and also because of the discrete nature of the model isochrones. Regarding the latter, it is well known that broad-band SED fitting results in artefacts in the

cluster age distribution. This is predominantly caused by specific features in the SSP models, such as the onset and presence of red giant branch or asymptotic giant branch (AGB) stars at, respectively, ~ 10 and ~ 100 Myr (e.g., Bastian et al. 2005). Alternatively, both the age-metallicity and the age-extinction degeneracies will affect the resulting cluster age distributions, thus also leading to artefacts in the data (e.g., de Grijs et al. 2003; Anders et al. 2004). We have attempted to avoid placing our age range boundaries around ages (and, where possible, have taken account of the uncertainties in age in doing so) where the effects of such artefacts might seriously impede the interpretation of the results. For instance, one can see a clear artefact in the cluster age distribution (which we will refer to as a ‘chimney’) at $\log(t/\text{yr}) \simeq 7.2$ ($\simeq 16$ Myr); the average uncertainties for these ages are of order a few Myr, so that we decided to limit our youngest cluster subsample to clusters younger than 10 Myr. If, instead, we had adopted an age limit at $\log(t/\text{yr}) = 7.17$ (15 Myr), we would have had marginally better statistics, but our analysis would be affected by the unknown effects of the age uncertainties associated with this chimney (see Goodwin et al., in prep., for a detailed discussion of the issues involved).

The rationale for adopting as our youngest subsample all clusters with ages ≤ 10 Myr is that at these young ages, the vast majority of the star clusters present will still be detectable, even in the presence of early gas expulsion (e.g., Goodwin & Bastian 2006) – as long as they are optically conspicuous. The CMF of this subsample is shown in Fig. 2a.

Fig. 2b includes our sample clusters with ages in excess of 40 Myr, up to 160 Myr. While the upper age limit ensures the full inclusion of the clusters affected by the onset of the AGB stage, its exact value is rather unimportant for our analysis, and it was mainly determined by the need to have reasonable statistics in this and the upper age range, shown in Fig. 2c. The lower age limit of this subsample is crucial, however. As shown by Goodwin & Bastian (2006), most dissolving clusters will have dispersed by an age of ~ 30 Myr, while the surviving clusters will have returned to an equilibrium state by ~ 40 Myr, when some of the early expansion will have been reversed, depending on the effective star-formation efficiency. This latter age is therefore a good lower boundary to assess the surviving star cluster population.

We explicitly exclude any star clusters aged between 10 and 40 Myr from our analysis. In this age range, it is likely that dissolving star clusters that will not survive beyond about 30–40 Myr might still be detectable and therefore possibly contaminate our sample. In addition, this is the age range in which early gas expulsion

causes rapid cluster expansion, before settling back into equilibrium at smaller radii; because of the expanded nature of at least part of the cluster sample, we might not be able to detect some of the lower-luminosity (and hence lower-mass) clusters that might again show up beyond an age of ~ 40 Myr. At the same time, the effects of ‘infant weightloss’ (Weidner et al. 2007) will further confuse the analysis in this age range.

The scaled canonical CMF in Fig. 2b is an almost perfect fit to the observed CMF. The best-fitting CMF slope is $d \log(M_{\text{cl}}/M_{\odot})/d \log(N_{\text{cl}}) = -0.82 \pm 0.18$, but this compares to $d \log(M_{\text{cl}}/M_{\odot})/d \log(N_{\text{cl}}) = -1.01 \pm 0.20$ if we ignore the lowest-mass clusters at $\log(M_{\text{cl}}/M_{\odot}) \leq 3.2$, where there may be residual incompleteness effects.

This very good match between the observed CMF for the age range from 40–160 Myr (Fig. 2b) and the scaled CMF from Fig. 2a implies that the *SMC* cluster system has not been affected by any significant amount of cluster infant mortality for cluster masses greater than a few $\times 10^3 M_{\odot}$. Based on a detailed assessment of the uncertainties in both the CMFs and the age range covered by our youngest subsample, we can limit the extent of infant mortality between the youngest and the intermediate age range to a maximum of $\lesssim 30$ per cent (1σ). We rule out a ~ 90 per cent mortality rate per decade of age at a $> 6\sigma$ level. This result is in excellent agreement with that of Gieles et al. (2007) – although we also note that Chandar et al. (2006) do not include the youngest *SMC* clusters in their analysis. Using the age distribution of the *SMC* cluster sample in units of the number of clusters observed per unit time-scale, we independently confirm this scenario (de Grijs & Goodwin 2007).

3 Dodgy diagnostics?

We now return to the use of the M/L ratio versus age diagram as a diagnostic tool. Despite the myriad uncertainties associated with its use, using this approach one can get at least an initial assessment as to whether a given cluster may be (i) significantly out of virial equilibrium, in particular ‘super-virial’, or (ii) significantly overabundant in low-mass stars. Since the ground-breaking work by Bastian & Goodwin (2006) and Goodwin & Bastian (2006), we can now also model any (super-virial) deviations from the SSP models for the youngest ages, if we assume that these are predominantly a function of the effective SFE.

This has led a number of authors to suggest that, in the absence of significant external perturbations, massive clusters located in the vicinity of the SSP models

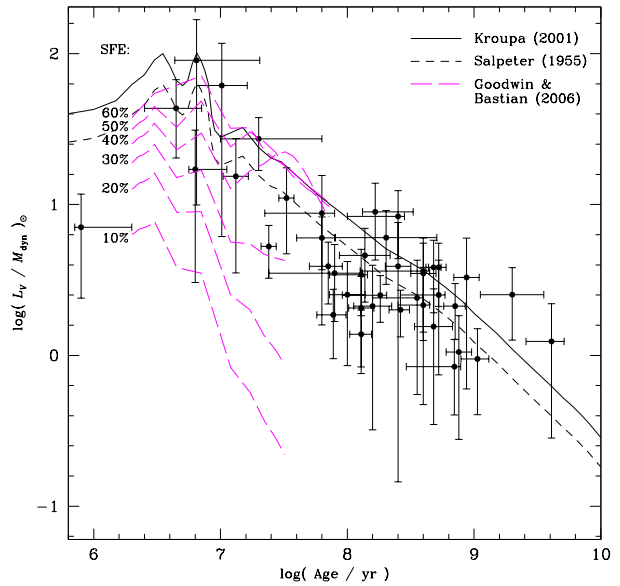


Fig. 3 Diagnostic age versus M/L ratio diagram, including the Galactic open clusters for which velocity dispersion measurements are available (adapted from de Grijs et al. 2008); the figure coding is as for Fig. 1

and aged $\gtrsim 10^8$ yr may survive for a Hubble time and eventually become old GC-like objects (e.g., Larsen et al. 2004; Bastian et al. 2006; de Grijs & Parmentier 2007).

Encouraged by the recent progress in this area based on both observational and theoretical advances, in de Grijs et al. (2008) we explore whether we can also use the same diagnostic diagram to assess the stability, formation conditions and longevity of those open clusters in the Milky Way for which the required observational data exist in the literature, and hence whether this approach might be useful in view of future data mining opportunities.

Using a sample of Galactic open clusters for which reasonably accurate internal velocity dispersions are available in the literature, we constructed a homogenised set of observational data drawn from a wide variety of publications, also including their most likely uncertainty ranges. This allowed us to derive dynamical mass estimates for our sample of open clusters, as well as their respective M/L ratios and – crucially – the associated (realistic) uncertainties.

Although our sample of Galactic open clusters is by no means statistically complete in any sense, this study has provided useful additional constraints on the dynamical state of the individual sample clusters. Compared to the photometric evolution predicted on the basis of Salpeter (1955) or Kroupa (2001)-type stellar

IMFs, this allowed us to independently assess the clusters' stability with respect to internal dynamical effects (and – to some extent – also to external perturbations).

Most importantly, we conclude that for an open cluster to survive for any significant length of time (in the absence of substantial external perturbations), it is a necessary but not a sufficient condition to be located close to the predicted photometric evolutionary sequences for 'normal' SSPs. This is highlighted using a number of our sample clusters which are known to be in a late stage of dissolution, yet lie very close indeed to either of the evolutionary sequences defined by the Salpeter (1955) or Kroupa (2001) IMFs. However, we also note that a significant fraction of our sample clusters show the signatures of dynamical relaxation and stability. Despite their relatively small masses ($M_{cl} \lesssim 2 \times 10^3 M_{\odot}$) and ages in excess of a few $\times 10^8$ yr, this is not unexpected. Using the vertical oscillation period, π , around the Galactic plane of NGC 2323 ($\pi \approx 50$ Myr; Clariá, Piatti & Lapasset 1998) as an example, this cluster has only been through a few of these periods, given its age of $\log(t/\text{yr}) = 8.11^{+0.05}_{-0.25}$ (Kalirai et al. 2003). However, at the Galactocentric distance of the Sun, a Pleiades-like open cluster crosses the Galactic disc approximately 10–20 times before it dissolves (de la Fuente Marcos 1998a,b).

Finally, we caution that for the low-mass Galactic open clusters in particular, the measured velocity dispersions may be significantly affected by the orbital motions of a sizeable fraction of binary or multiple systems (e.g., Kouwenhoven & de Grijs 2008). In a follow-up paper (Kouwenhoven et al., in prep.) we will explore this quantitatively using N -body simulations.

4 'Super' star cluster survival confirmed?

We recently reported the discovery of an extremely massive, but old (12.4 ± 3.2 Gyr) GC in M31, 037-B327, that has all the characteristics of having been an exemplary YMC at earlier times, based on an extrapolation of its present-day extinction-corrected V -band luminosity back to an age of 10 Myr (Ma et al. 2006b; see also Cohen 2006). To have survived for a Hubble time, we concluded that its stellar IMF cannot have been top-heavy. Using this constraint, and a variety of SSP models, we determined a *photometric* mass for 037-B327 of $M_{GC} = (3.0 \pm 0.5) \times 10^7 M_{\odot}$, somewhat depending on the SSP models used, the metallicity and age adopted and the IMF representation. In view of the large number of free parameters, the uncertainty in our photometric mass estimate is surprisingly small (although this was recently challenged by Cohen 2006).

This mass, and its relatively small uncertainties, make this object potentially one of the most massive star clusters of any age in the Local Group. Based on a more recent dynamical mass determinations by Cohen (2006), it appears that 037-B327 may be a factor of $\sim 2-3$ less massive than M31 G1, assuming that both GCs have the same stellar IMF. Nevertheless, this still confirms the nature of 037-B327 as one of the most massive star clusters in the Local Group. As a surviving 'super' star cluster, this object is therefore of prime importance for theories aimed at describing massive star cluster evolution.

Cohen (2006) suggests that the high mass estimate of Ma et al. (2006b) may have been affected by a non-uniform extinction distribution across the face of the cluster (see also Ma et al. 2006a for a more detailed discussion). She obtains, from new K -band imaging and different assumptions on the extinction affecting the K -band light, that M_K of 037-B327 may be some 0.16 mag brighter than that of M31 G1, or about twice as luminous. Despite these corrections provided by Cohen (2006), the basic conclusion from Ma et al. (2006b), i.e., that at the young age of 10 Myr cluster M31 037-B327 must have been a benchmark example of a 'super' star cluster, and that its IMF must thus have contained a significant fraction of low-mass stars, still stands firmly.

Thus, in summary, the formation of GCs, which was once thought to be limited to the earliest phases of galaxy formation, appears to be continuing at the present time in starburst, interacting and merging galaxies in the form of star clusters with masses and compactnesses typical of GCs. Whether these YMCs will evolve to become old GCs by the time they reach an age of 13 Gyr depends to a very large extent on their environment, however. For a host galaxy with a smooth logarithmic gravitational potential, the ambient density seems to be the key parameter driving the rate of cluster evolution. This is accelerated in the presence of substructure in the host galaxy, such as that commonly provided by bulge, spiral arm and giant molecular cloud components (see also the review of de Grijs & Parmentier 2007, and references therein).

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